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Technical Information Division, ORE, Oak Ridge, Tennessee

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# MAGNETIC-AMPLIFIER VOLTAGE REGULATOR

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## ABSTRACT

This paper covers the development and testing of a regulated power supply which uses a magnetic amplifier as the regulating element. Circuitry considerations for a simple regulating system are presented and applied to the magnetic-amplifier regulating system. The performance of the regulated power supply has been found to be very satisfactory for general electronic-supply purposes.

The reference for the magnetic amplifier is obtained by means of a parallel linear-nonlinear resistive network from which deviations in output voltage are fed back magnetically to the primary circuit. The impedance of the magnetic amplifier in the primary circuit controls the voltage applied to the transformer primary. Fluctuations in load current are detected by means of a control winding in series with the load.

The power supply will regulate at 160 to 400 volts within 0.5 per cent for load currents from 0 to 500 ma (line-voltage constant), and within 0.5 per cent or less for ±10 per cent change in line voltage and load currents from 0 to 300 ma, or within 1 per cent or less for ±20 per cent change in line voltage and load currents of 0 to 300 ma.

The performance of the power supply was observed for ambient temperatures from 0 to 55°C. The changes in regulation properties of the unit were found to be virtually negligible over the above temperature range.

## INTRODUCTION

The purpose of this project was to develop a regulated power supply giving a stabilized d-c voltage for general electronic usage. The voltage regulator and the power supply were to be as reliable as possible and were to contain no vacuum tubes.

This report covers the design and testing of such a unit to meet the following specifications: The output voltage was to be regulated at 200 to 300 volts within 1 per cent or less for ±10 per cent change in the 115-volt 60-cycle line voltage and load currents from 0 to 300 ma. The power supply (Figs. 9, 10, 11, and 12) resulting from this project actually regulates at 200 to 300 volts within 0.5 per cent for load currents from 0 to 500 ma (line-voltage constant), and within 0.5 per cent or less for ±10 per cent change in line voltage and load currents from 0 to 300 ma, or within 1 per cent or less for ±20 per cent change in line voltage and load currents of 0 to 300 ma.

There are a number of reasons for the demand for a regulated power supply as specified above containing no vacuum tubes. As compared with the vacuum-tube amplifier, the magnetic amplifier provides a rugged and reliable means of amplification. In applications where the frequency response is not too important, or for d-c amplification, the magnetic amplifier offers many advantages. It requires no filament power, and no warming period and has greater life expectancy. The magnetic amplifier can be made as sturdy as the mounting components, and the life is almost indefinite. It is practically shockproof, and maintenance costs are negligible. The ideal efficiency of the magnetic amplifier is unity, but that of a vacuum tube is considerably less because the magnetic amplifier functions as a variable reactance whereas the vacuum tube functions as a variable resistance.

## DESIGN OF MAGNETIC AMPLIFIER

An investigation of the characteristics of magnetic amplifiers with particular regard to maximum gain and power-handling capacity was carried out. It became apparent that a core configuration having no air gap and a magnetic core material having a relatively low coercive force at the knee of its magnetization curve would appreciably improve the amplification. A high-working flux density was also considered to be important to give a relatively smaller device for a given power-handling capacity. Consideration of the characteristics and availability of various magnetic materials indicated that a strip-wound uncut (toroidal) hipersil core would produce a satisfactory amplifier for this regulation problem. Some of the properties of hipersil that contributed to its selection as the core material for this unit are its high-flux carrying capacity, having a high permeability at high inductions, and its relative insensitivity to mechanical strain. It is rugged by comparison to some of the square loop materials and high-permeability high-nickel alloys. The properties of hipersil do not tend to change with time and change very little with handling. Hipersil exhibits much less ageing than the hot-rolled silicon steels and is available at relatively low cost.

The design of the core itself was considerably complicated by the fact that the load on the regulator changes by a factor of 10 or more (assuming a 50-ma bleeder current) over the prescribed range of regulation for this device. This feature was very serious, because the amplifier must regulate for 10 per cent changes in line voltage over this range of load resistance. The amplifier was designed so that the initial operating point (zero control current) lies just below the knee of the magnetization curve of the magnetic material so as to obtain maximum output per pound of core material. Since

$$\frac{B \alpha E}{NA} = \text{volts/turn sq in.}$$

and

$$\frac{H \alpha NI}{\ell} = \text{ampere turns/in.}$$

where E = a-c reactor volts
N = a-c turns
A = cross-sectional area of core
$\ell$ = length of magnetic path
I = reactor alternating current

(direct current assumed constant), the magnetization curve for the core material can be reduced to a curve of reactor a-c voltage vs. reactor alternating current for fixed direct current in control windings. The data are applicable to any core of this material regardless of size and coil configuration if the effects of the ratio of inner diameter to outer diameter and leakage with different core sizes and shapes are neglected.

Since the initial operating point has been determined as above, the first conditions on N, A, and $\ell$ of the core have been found. Additional relations among these quantities were obtained from a consideration of the basic circuit to be used, i.e., current density, wire size, number of turns, and power dissipation, since they affect the winding space and the heat-radiating surface required.

A consideration of the above factors resulted in a magnetic core as follows:
Core material, hipersil.
Tape thickness, 0.013 in. (suitable for 60 cycles).
Tape width, 1 in.
Build-up, ½ in.
Core area, ½ sq in.
Length, 12.6 in. (mean circumference).
Inner diameter, 3.5 in.
Outer diameter, 4.5 in.
AO windings, 880 turns of AWG No. 18 wire per core.

Figure 1 is a diagram showing the manner in which the two magnetic cores were wound and oriented. There were two a-c windings of 880 turns each of AWG No. 18 wire (one winding per core), and three d-c control windings (number of turns to be given later in this report) and two so-called additional feedback windings; all were wound as shown in Fig. 1. This amplifier was found to have an average power gain of the order of $10^6$ with a load resistance of 10 ohms at a power level of 0.5 to 360 watts.

The transfer curve ($NI_{ac}$ vs. $NI_{dc}$) for fixed load resistance and fixed a-c voltage for the magnetic amplifier was obtained by superimposing on the reactor a-c voltage vs. alternating current curves an operating locus for each value of load resistance. A family of transfer curves for the magnetic amplifier of this project is shown in Fig. 2. All the steady-state output characteristics of the amplifier can be obtained or calculated from the transfer curves.

## CIRCUITRY

The basic operation of the voltage regulator can best be understood from Fig. 3, which is a block diagram of a simple regulating system. The voltage of the output device, B, is measured by the error detector, C, and compared with a reference quantity, E. The difference between the reference quantity and the output is fed to the error-correcting device, A, and a signal of the proper sense and magnitude is applied to the output device, B, such that the error is reduced toward zero. Such regulators usually include an operator's control, D, which allows arbitrary selection of the output voltage. Any selected voltage within limits is automatically regulated by the closed system.

In the regulated power supply under discussion, the error detector and reference quantity are incorporated in a single parallel circuit (Fig. 4) containing a linear resistance in series with one d-c control coil (1000 turns of AWG No. 33 wire) and a nonlinear resistance (six thyrites in parallel) in series with a second oppositely connected d-c control coil (5000 turns of AWG No. 33 wire). At the voltage, $E_0$ (see Fig. 4), across this linear-nonlinear parallel network, the two control coils are contributing approximately the same ampere turns, NI, in opposite senses so that the resultant is that required for the optimum quiescent operating point. If the output voltage, E or $E_0$, rises, the $N_2I_2$ (neg.) increases nonlinearly (very fast), while $N_1I_1$ (pos.) increases linearly (very slowly), so that the resultant $NI_{dc}$ increases negatively. As will be seen later in this report, this negatively increasing $NI_{dc}$ will decrease the $NI_{ac}$. Hence, the transformer-primary voltage and the output voltage, which originally was too high, will be decreased (see Fig. 5). If the output voltage should drop, the opposite effect takes place, with a resulting increase in the output voltages from the regulator action. Thus, the linear resistor can be considered as the reference, E; and the nonlinear branch, the error detector, C. The operator's control, D, is the variable resistor, $R_1$, in series with the parallel reference–error detector network. $R_1$ and $R_2$ are so established that both $I_1$ and $I_2$ (linear and nonlinear currents) remain essentially constant as $R_1$ is varied. Thus, the operating point of the nonlinear device as well as that of the magnetic amplifier are maintained, but the output voltage is varied within prescribed limits (200 to 300 volts) by changing $R_1$. The voltage across the parallel network, $E_0$, then must be considerably less than 200 volts. In actual operation, $E_0$ is approximately 140 volts to allow the output voltage to be varied from 300 to 200 volts with ease.

The complete schematic diagram for the regulated power supply is shown in Fig. 5. It will be assumed that the reader is familiar with the theory of operation of magnetic amplifiers, and no detailed description of this operation will be given in this report.

The primary circuit consists of the a-c coils of the magnetic amplifier in series with the primary of the transformer $T_1$. The operation of the primary circuit can be thought of in terms of an equivalent circuit consisting of a variable inductive reactance in series with a variable resistance (transformer primary) connected across a variable line voltage (±10 per cent). It is essential for satisfactory regulation that the voltage across the transformer primary be maintained approximately constant. The load coils of the magnetic amplifier are connected in conjunction with the feedback rectifiers to form a self-saturation or self-feedback type of magnetic amplifier. The principle underlying self-saturation is that the output current, or part thereof, is used to amplify the effect of the control current, thereby reducing the power required by the control windings. The advantage in paralleling the a-c coils is the resulting availability of positive feedback for greatly increased gain without requiring any additional windings on the core, simply by inserting two half-wave rectifiers, as shown in Fig. 5. This self-saturation principle can be employed in any application where time response is not of utmost importance.

The feedback rectifiers already mentioned are 24-volt selenium disks, 4⅛ in. in diameter (4 amp), connected eight in series per each half-wave section. These rectifier disks are operated at much below their rated inverse voltage to make the inverse leakage current essentially negligible. It has been found that inverse leakage currents of 1 per cent or more are seriously detrimental to the sensitivity of the amplifier. Self-saturating circuits may have external or additional feedback to compensate for rectifier leakage. Such additional feedback was provided in this magnetic amplifier, wound as shown in Fig. 1, and connected as shown in Fig. 5. However, better results were obtained by minimizing the rectifier leakage by inserting more disks in series to the extent that additional feedback was not needed.

The magnetic amplifier actually consists of two identical iron-core transformers with the winding polarities such that the fundamental frequency voltages induced in the control windings are minimized. It is very important that there be as little current as possible in the thyrites from induced voltages in the control windings in order to avoid heating.

The full-wave bridge rectifier across the secondary of transformer $T_1$ consists, also, of 24-volt selenium disks, 1⅜ in. in diameter. Here, the rectifier inverse leakage current is of secondary importance; therefore the rectifiers are operated at rated voltages. For stability reasons, the filter consists only of a large capacitance (350 $\mu$f). The maximum ripple in the output is less than 1 per cent. It was found that the presence of a choke in the filter resulted in an additional time lag in the regulating loop. This lag was directly responsible for an oscillatory condition of the system. The control winding, $W_3$ (10 turns of AWG No. 33 wire), functions as a load compensating winding. It is so oriented on the core and so connected in the circuit that an increase in load current through it results in an increase in the transformer-primary voltage to compensate for the increased internal-voltage drop. The output voltage is therefore held essentially constant for all load currents within the prescribed limits (see Fig. 8). It was found necessary to add a capacitance across the thyrites to minimize the flow of harmonic currents through them. The value of capacitance of 0.5 $\mu$f was a compromise between perfect shunting of the harmonic currents and maximum sensitivity of the system.

It was considered desirable to include in the power supply a bias as well as a filament supply in order to make the supply more useful for laboratory testing. These additional supplies have no connection with the original project and are mounted on the same chassis for convenience only. The filament supply consists merely of a 6.3-volt center-tapped transformer rated at 10 amp (see Fig. 5).

The bias supply provides a variable negative (or positive) regulated voltage from 0 to 105 volts. The regulation of the 105 volts is achieved by the use of a VR-105 tube with appropriate filtering. The voltage-regulator tube operates at 30 ma so that load currents up to 20 ma are available at 105 volts with satisfactory regulation. No special provision is made in the circuitry for regulation at lower voltages for appreciable load currents.

## PERFORMANCE

The performance of this unit has been very satisfactory. The regulation data are presented in the curves of Figs. 6, 7, and 8. The method of data taking was to permit variation in only one quantity while all others were held constant. For instance, Fig. 6 is a graph of output voltage against line voltage for a fixed load current (0 ma) and a fixed position of the operator's voltage control. Curves are shown for an output voltage of 200 and 300 volts. Also shown is an expanded graph of the curves of Fig. 6 for line volts within the ±20 per cent range. Figure 7 shows the same curves except for a load current of 300 ma. Figure 8, on the other hand, shows the load characteristics, i.e., output voltage against load current for fixed line voltage.

Regulation data taken on the three units constructed were found to coincide within a small fraction of a per cent over the entire range of line voltage (0 to 135 volts) and load current (0 to 500 ma) covered.

Photographs of the complete power supply are shown in Figs. 9, 10, and 11. Figure 12 is a photograph of the magnetic amplifier alone. Three terminals (positive, negative, and ground) have been provided for the high-voltage supply as well as for the bias supply. This permits a great deal of flexibility in that either a plus or minus, grounded or ungrounded, voltage is available from both supplies.

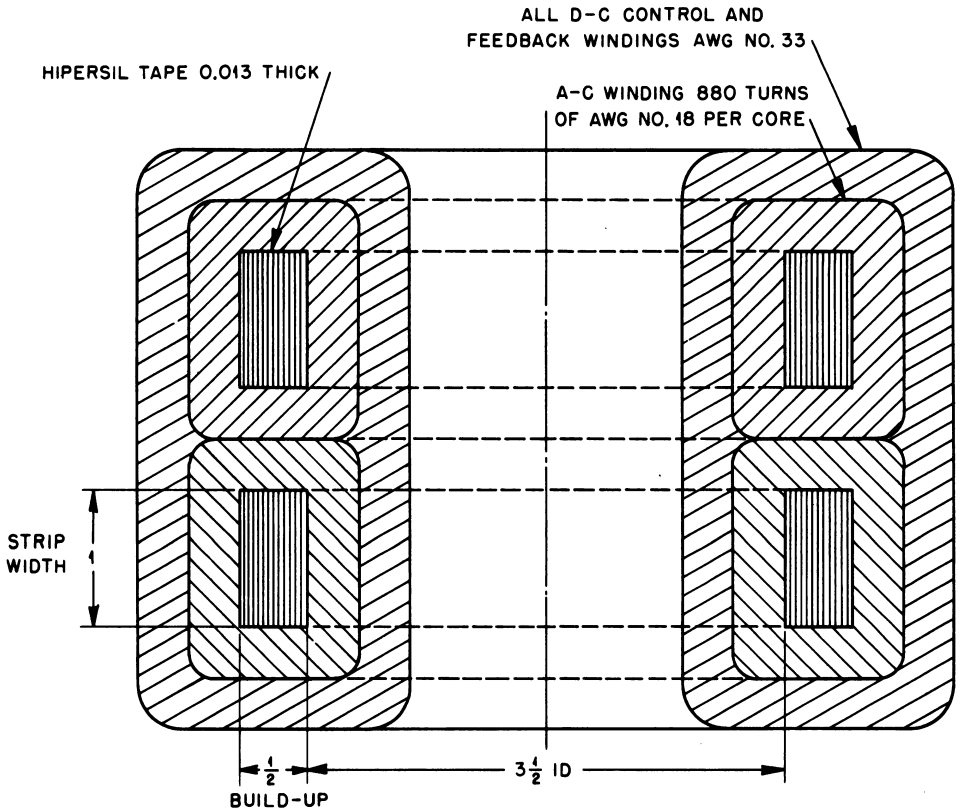


Fig. 1 —Construction of the magnetic amplifier (actual size). The a-c windings are distributed along the cores. However, the d-c windings are concentrated but are wound consecutively along the cores in order to cover the cores circumferentially.

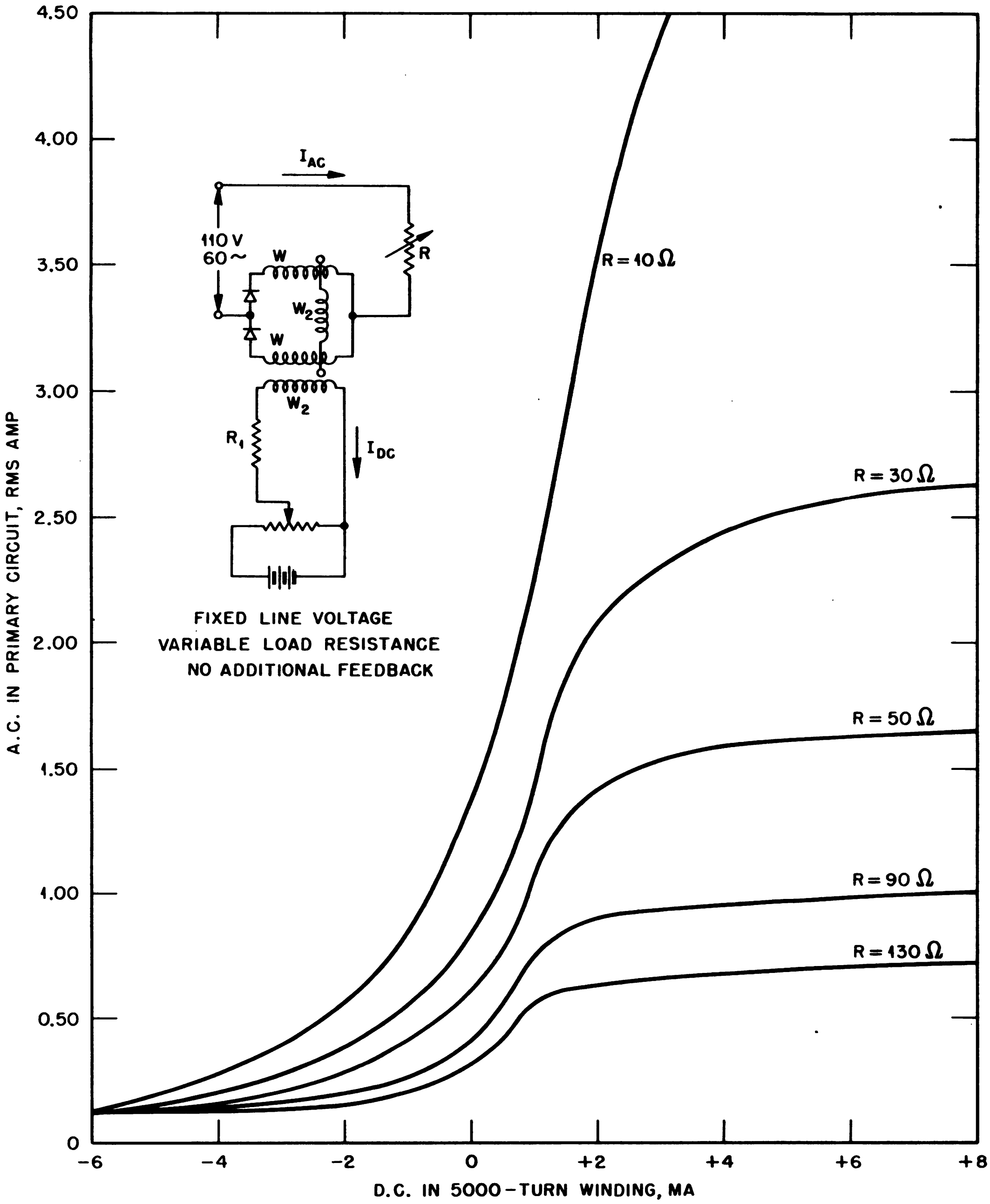


Fig. 2—Transfer characteristics of magnetic amplifier.

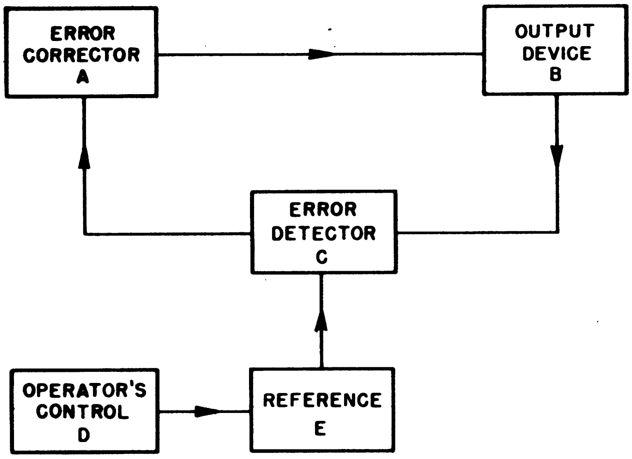


Fig. 3—Block diagram of simple regulating system.

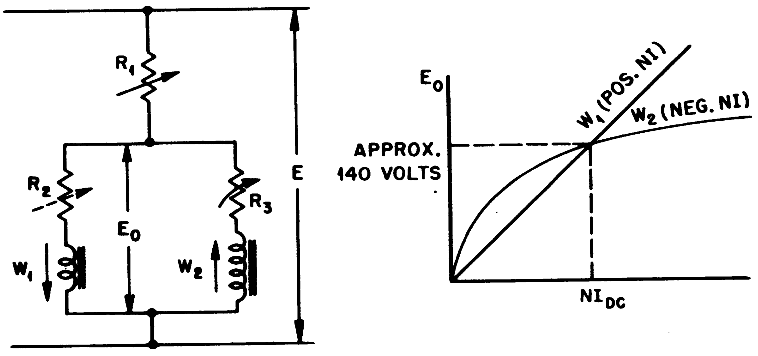
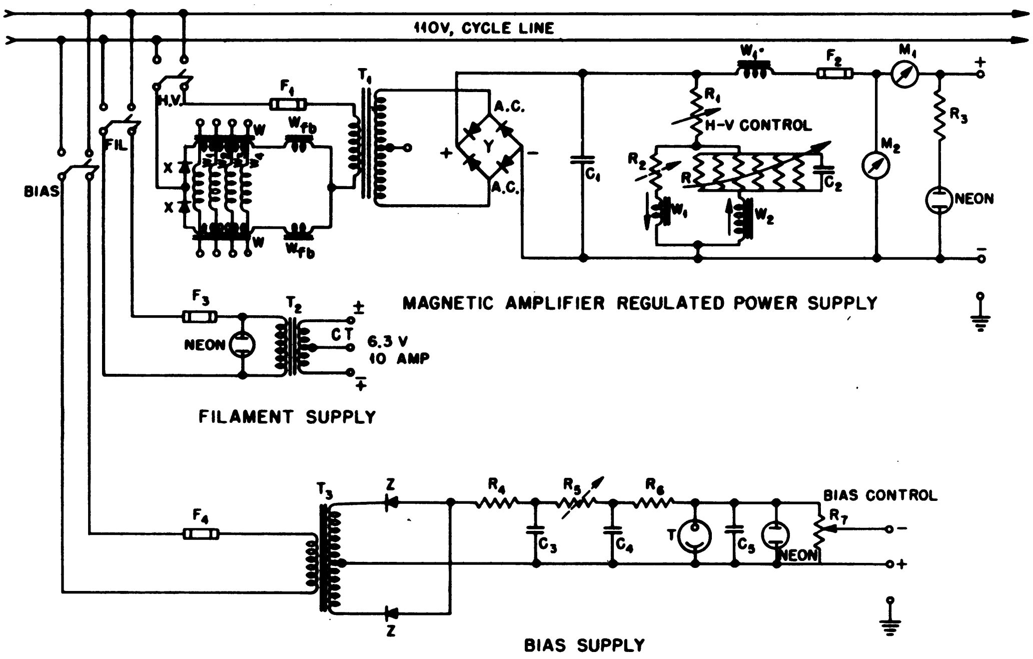


Fig. 4—Schematic diagram of error detector-reference network. $R_1$, operator's control on front panel, permits adjusting E, regulated output voltage, to desired level. $R_2$, chassis screw-driver adjustment, is made adjustable to permit tilting of the $W_1$ curve so that the intersection of the $W_1$ and $W_2$ curves occurs at an appropriate voltage $E_0$ and/or slope of $W_2$ curve. $R_3$, nonlinear resistance.



### Magnetic-amplifier High-voltage Supply

$F_1$, 8-amp fuse
$F_2$, 0.5-amp fuse
$T_1$, Thordarson transformer 12-T-22R35 110/400-0-400, 340-ma direct current
X, Half-wave rectifiers, eight 4¾ in. selenium cells in series
Y, Full-wave bridge rectifier, twelve 1¾ in. selenium cells per section
$M_1$, 0 to 500-ma 3-in. panel ammeter
$M_2$, 0 to 500-volt 3-in. panel voltmeter
Note: In actual operation, $W_{fb}$ = 0; and $W_3$ = 10 turns

$C_1$, Three Sprague TVL-6 dry electrolytic condensers, 450 volts, 125 μf each
$C_2$, Paper condenser, 0.5 μf 400 volts
$R_1$, Ohmite, 5 K, 100 watts
$R_2$, Ohmite, 5 K, 100 watts
$R_3$, 150-K 1-watt resistor
R, Six thyrites, type No. 8355083G1
W, Windings, ac, 880 turns of AWG No. 18 each
$W_{fb}$, Feedback windings, 50 turns (with taps) of AWG No. 18 each
$W_1$, Control winding, 1000 turns of AWG No. 33
$W_2$, Control winding, 5000 turns of AWG No. 33
$W_3$, Control winding, 100 turns (with taps) of AWG No. 22
Neon, NE-51 assembly

### Filament Supply

$F_3$, 1-amp fuse
Neon, Ne-51 assembly

$T_2$, Thordarson transformer 12-T-21F12, C.T. 6.3 volts, 10 amp

### Bias Supply

$F_4$, 0.5-amp fuse
$T_3$, Thordarson transformer 12-T-22R00 110/250-0-250, 40-ma direct current, Pri. volt-amp 45
Z, Half-wave selenium reactifiers, 100 ma, 130 volts
Neon, NE-51 assembly

$C_3$,$C_4$, Electrolytic condensers, 40 μf, 250 volts
$C_5$, Paper condenser, 1 μf, 600 volts
$R_4$, Resistor 47 Ω, ½-watt
$R_5$, Ohmite, 5 K, 25-watt rheostat (chassis screw-driver adjustment)
$R_6$, Resistor, 100 Ω, ½-watt
$R_7$, 50 K, 4-watt pot. (front panel)
T, OC3-VR-105 vacuum tube

Fig. 5—Over-all schematic diagram of magnetic-amplifier regulated power supply.

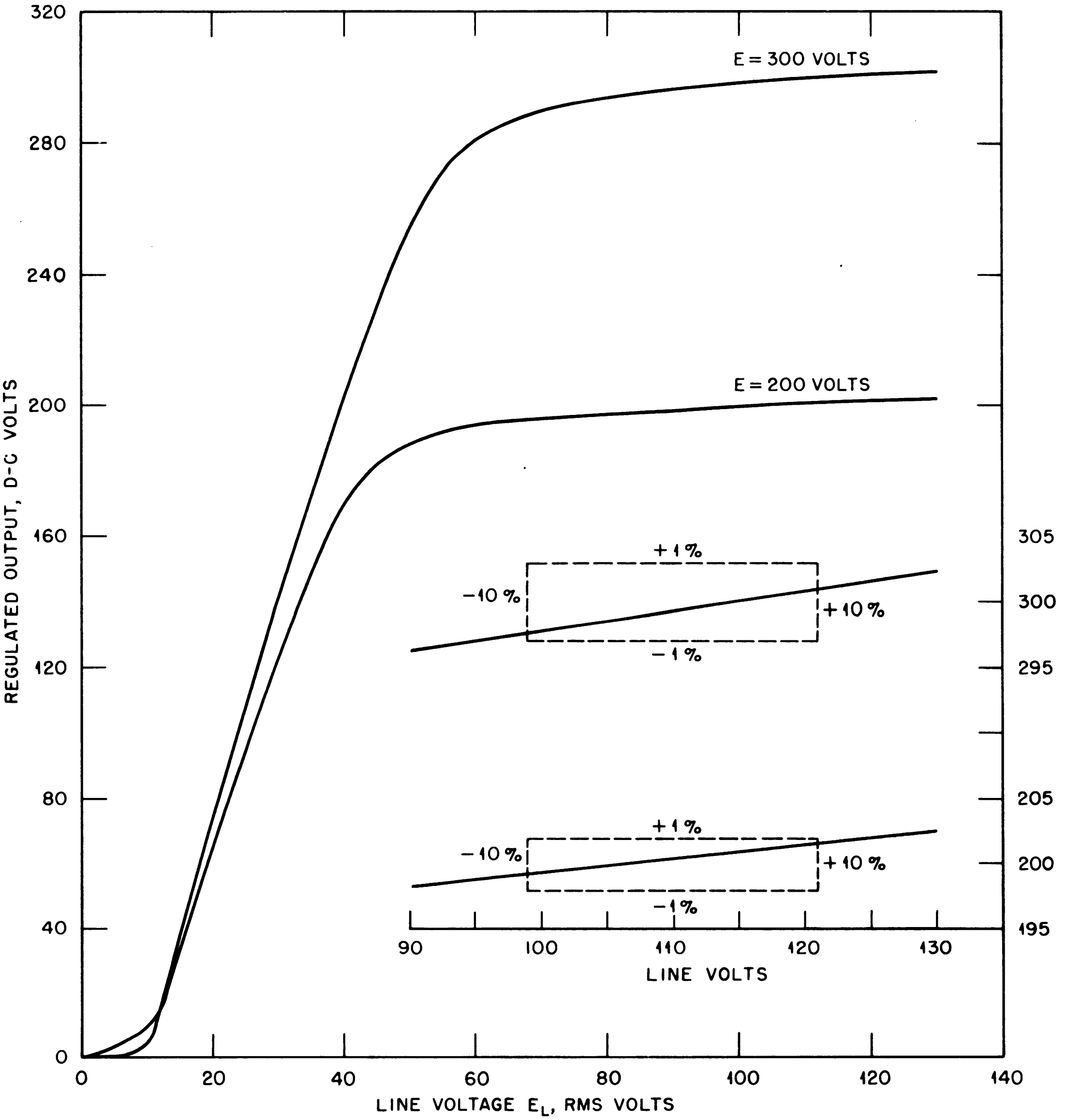


Fig. 6 —Regulation against line voltage (zero load current).

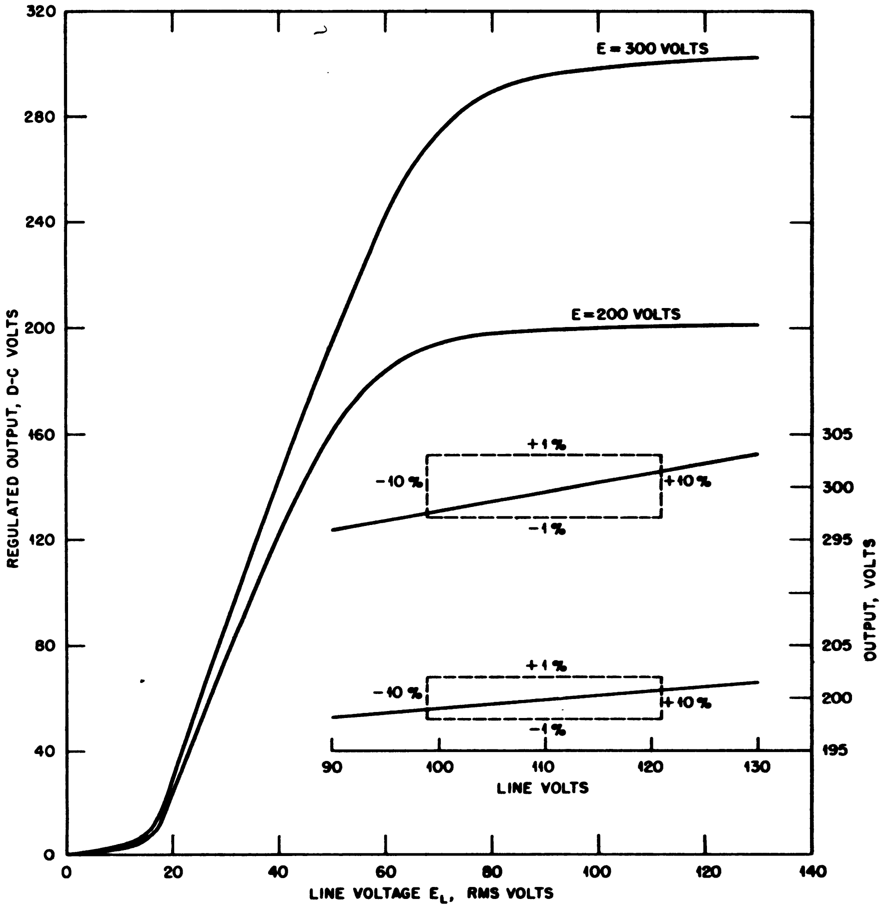


Fig. 7—Regulation against line voltage (300-ma load current).

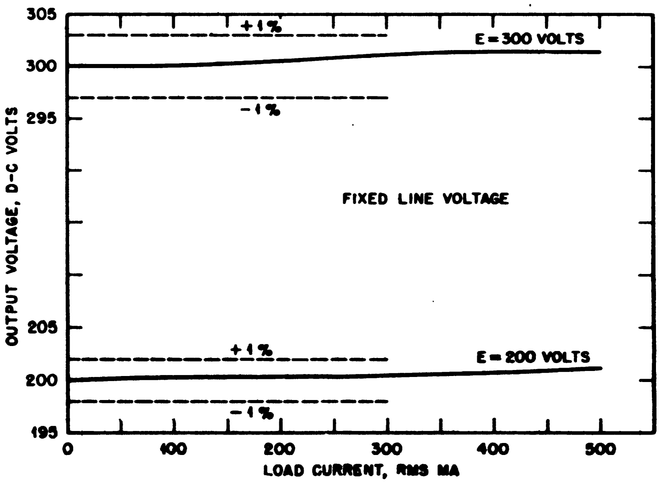


Fig. 8—Regulation against load current.

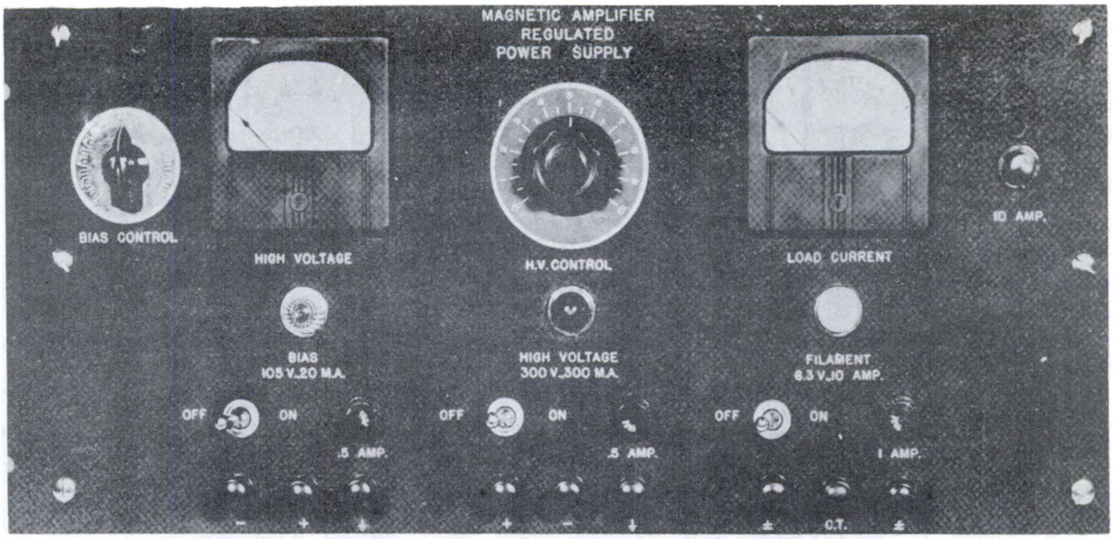


Fig. 9 — Front-panel view of magnetic-amplifier regulated power supply.

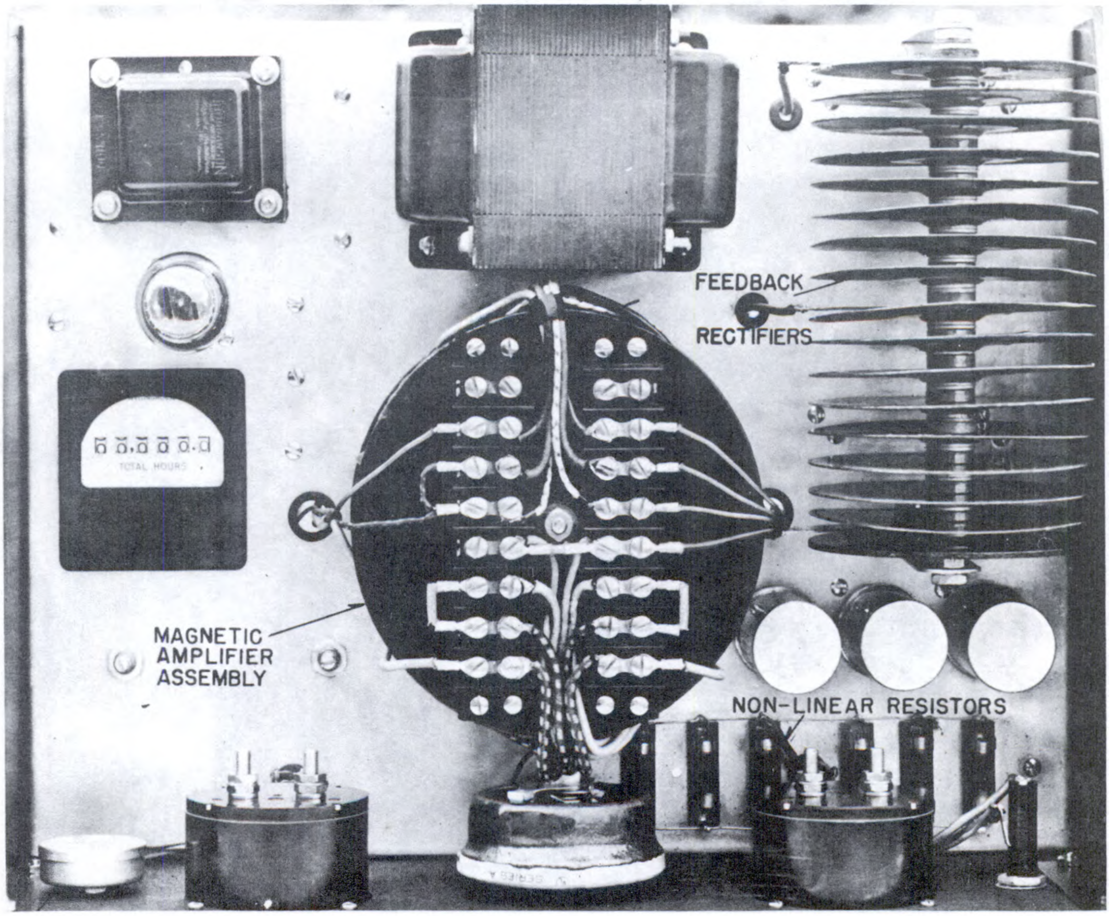


Fig. 10 — Top view of magnetic-amplifier regulated power supply.

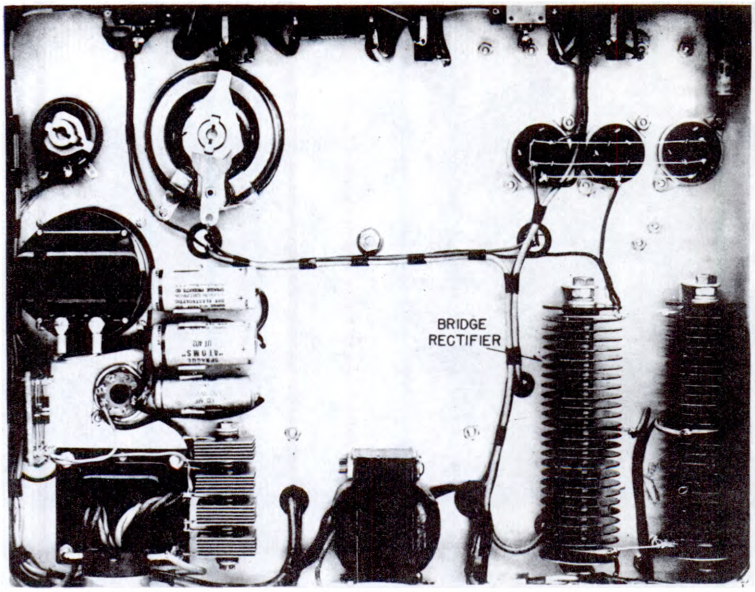


Fig. 11 — Bottom view of magnetic-amplifier regulated power supply.

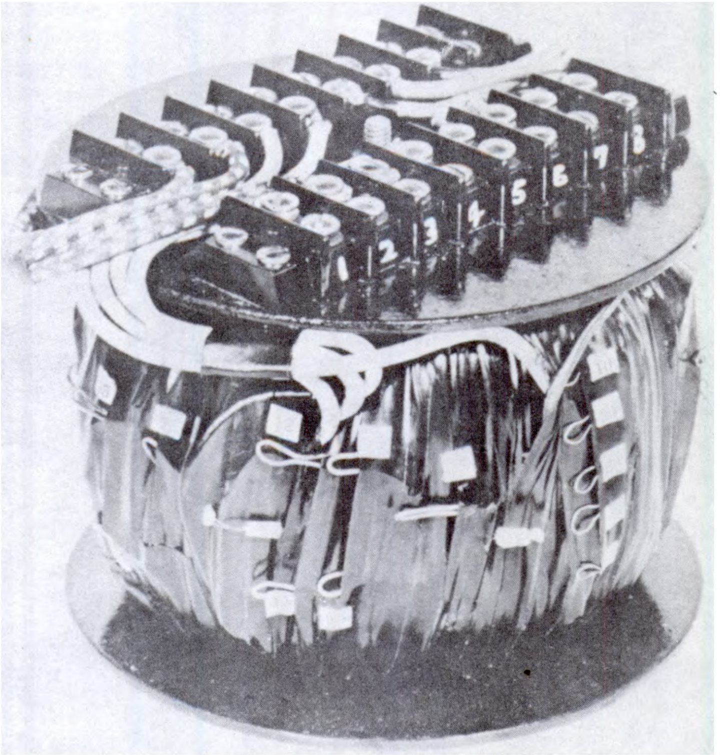


Fig. 12 — Magnetic amplifier used as the regulator in the regulated power supply.

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